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ESTIMATED TEMPERATURES OF EBR-II FUEL CYCLE FACILITY SHIELDING WINDOWS AT GAMMA RADIATION LEVEL OF 3.5×10^5 rad per hour

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9700 South Cass Avenue
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T. W. Eckels and L. F. Coleman

Chemical Engineering Division

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ESTIMATED TEMPERATURES OF EBR-II FUEL CYCLE FACILITY SHIELDING WINDOWS AT GAMMA RADIATION LEVEL OF 3.5×10^5 rad per hour

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SUMMARY

Calculations have been made of the transient and steady-state temperatures which may be expected to occur in EBR-II Fuel Cycle Facility shielding windows subjected to gamma radiation. The limiting assumptions are stated, and observations are made of the temperature effects of installing a 1/4-in.-thick glass cover plate over the exposed surface of the heavy glass slab that is at the hot side of each window. The window temperature which will result from a proposed schedule of opening and closing a 6-in.-thick steel shielding shutter are also discussed.

INTRODUCTION

The Fuel Cycle Facility (see Fig. 1) for Experimental Breeder Reactor No. II (EBR-II) has 31 5-ft-thick shielding windows, costing approximately $750,000. Most of the operations performed in the air-atmosphere cell (Air Cell) and argon-atmosphere cell (Argon Cell) will be viewed through these windows.

The shielding windows each consist of four major glass components (see Fig. 2). Proceeding from the inside or hot face of the cell, these components are:

1. A remotely removable, hinged, steel-framed, dry pane designated Slab A. The glass is $36\frac{1}{2}$ by $36\frac{1}{2}$ by $9\frac{1}{16}$ in. Should the light transmission of the glass in the hinged pane decrease significantly due to radiation darkening, this hinged assembly may be remotely removed and replaced, using a cell crane and manipulator.

2. A remotely removable, steel-framed, dry pane designated Slab B. The glass is 29 by 31 by $9\frac{1}{16}$ in. Should this pane darken, it also may be remotely removed and replaced; however, a special jig must be used. During replacement of inner panes, the seal plate (C) and the tank unit (D, E, F, G, H, J) would provide a seal and adequate shielding.

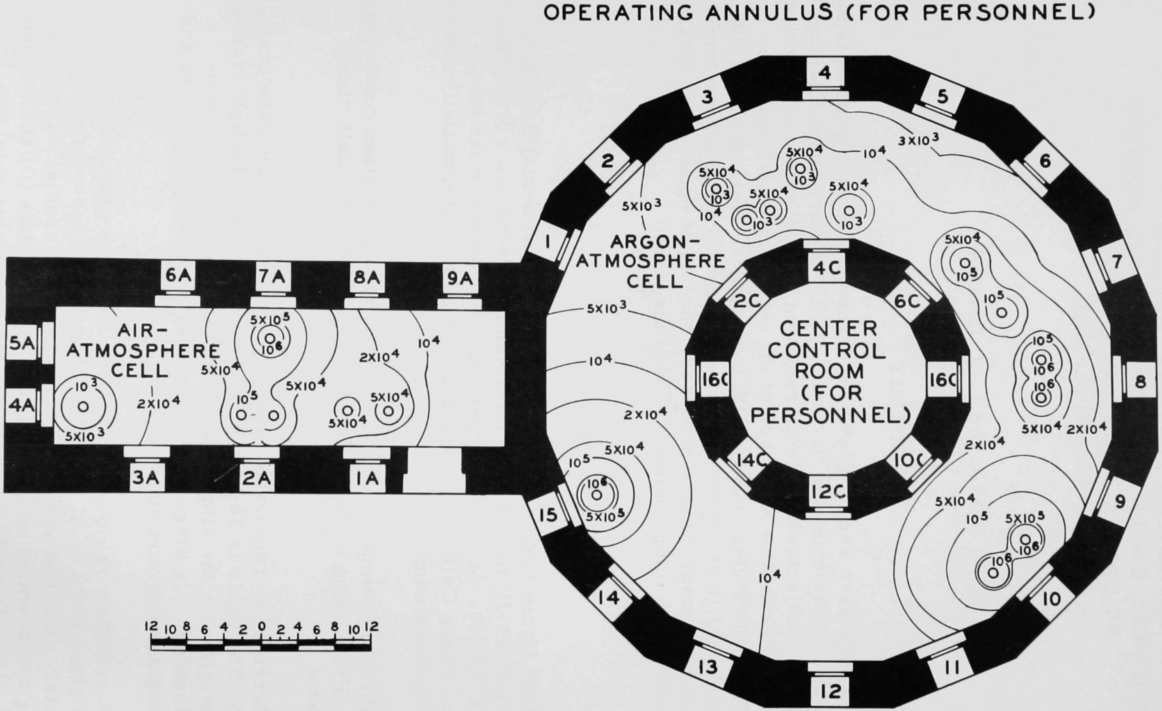

Fig. 1. EBR-II Fuel Cycle Facility. (Numbers indicate estimated gamma radiation intensity, rad/hr, near fuel processing equipment.) The Fuel Cycle Facility consists primarily of (1) an argon-atmosphere cell (designated the Argon Cell), approximately of 62-ft inside diameter, where fuel processing is done, (2) an adjacent air-atmosphere cell (designated the Air Cell), 16 ft wide by 45 ft long, where reactor subassemblies are assembled and disassembled, (3) an operating annulus which surrounds the two cells, and (4) a central control room. The object of the facility is to demonstrate the continuous reprocessing of multikilogram quantities of spent EBR-II reactor fuel which has been cooled only 15 days after removal from the core of the reactor. Because of the high levels of radioactivity, the fuel-handling and processing equipment is designed for remote operation which is accomplished with the aid of bridge cranes and manipulators.

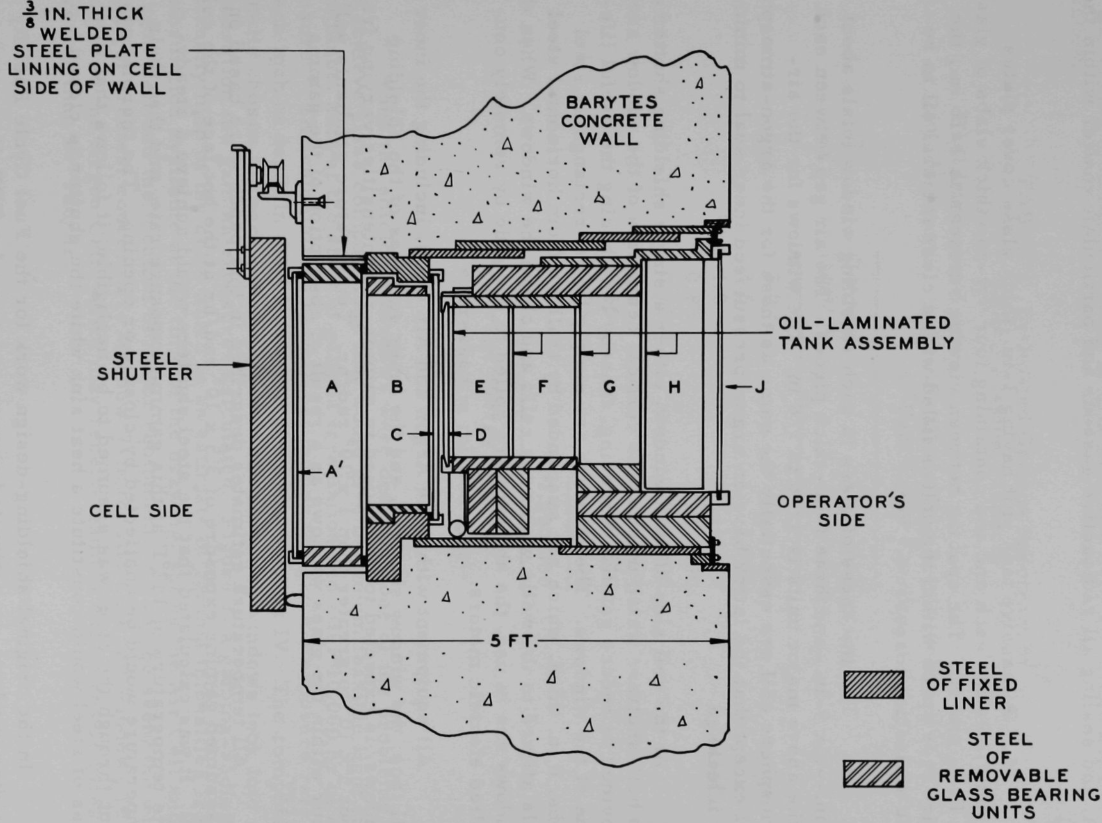

Fig. 2. Vertical Section of Fuel Cycle Facility Shielding Window

3. A glass seal plate, $34\frac{1}{2}$ by $36\frac{1}{2}$ by 1 in. thick, designated C. This plate is also dry; it is gasketed and provides the primary gas seal for the window opening maintaining the atmosphere of the argon-atmosphere cell, and sealing all radioactive gaseous and particulate matter within the cell.

4. A massive tank unit having 1-in.-thick glass cover plates (D and J) sealing each end and containing four $9\frac{1}{16}$-in.-thick slabs of glass (E, F, G, and H). The spacing between viewing surfaces is 1/16 in.; the entire free space within the unit is filled with a clear mineral oil to reduce reflection losses.

The thickness of glass in each shielding window totals about 57 in.--six 9-in.- and three 1-in.-thick pieces. The air gap between each of the above major units is 1/16 to 1/8 in. The windows for the air-atmosphere cell are essentially the same as those for the argon-atmosphere cell except that the latter have an argon-pressurized inner seal to minimize air inleakage.

At the cell side of each window, either a single shielding shutter or two half-shutters which meet at the vertical centerline of the window are provided to reduce gamma darkening, thereby lengthening the useful lifetime of the windows. The shutters are simply large, rectangular steel slabs, 6 in. thick, which are suspended by trolleys from horizontal steel rails affixed to the walls within the cells and above the windows. When the windows are in use, the shutters are rolled to one side by remotely controlled electric motors.

All equipment within the Argon and Air Cells, including the inner wall face, the window shutters, and the inner surfaces of the shielding windows, is expected to be exposed to gamma-ray intensities varying from about 5×10^3 to greater than 1×10^5 rad/hr. Temperature gradients will occur within the glass windows as a result of absorption of the gamma energy.

All temperature estimates described in this paper were based on an assumed gamma exposure of 3.5×10^5 rad/hr at the hot face of the cell wall. It was calculated that the steel shutters would achieve a steady-state temperature of 147°F at this gamma exposure rate, and that their temperature would be unaffected by closing or opening. The thermal gradient through the steel was assumed to be negligible; it follows that the mass of steel would constitute a heat sink while the shutter is closed.

In the original shielding-design work for the Fuel Cycle Facility shielding windows, an estimated gamma spectrum for EBR-II reactor fuel fission products was calculated.[1] Table I shows the energy distribution for an assumed exposure rate of 1×10^6 rad/hr. For convenience in calculations, it was further assumed that the radioactive source would be capable of delivering a collimated beam of this intensity over the whole area of the window.

TABLE I. Estimated Gamma Spectrum of EBR-II Fission Products

Fuel burnup to 2 a/o in 135 days: 15-day cooling before delivery to Fuel Cycle Facility

Gamma (MeV)[a]	Exposure (rad/hr)
3.0	40
2.5	2,060
1.0	141,000
0.85	39,300
0.75	564,000
0.5	190,600
0.35	50,500
0.06	12,500
	1,000,000

[a]Average energy of group expressed in million electron volts.

When the shielding windows were designed, one of the problems was to achieve glass compositions that would give maximum feasible light transmittance, both at the start of gamma irradiation and after 10,000 hr of exposure.* The calculations used in estimating the gamma exposure rate at each inch of depth in the window are given in Appendix IV. The composition finally chosen for each pane of glass in the shielding windows took into consideration the gamma exposures calculated. Figure 1, a gamma-radiation-intensity map of the cells which is an estimate of gamma intensities from information available at the time of the drawing, shows the Air Cell and Argon Cell and the location of major equipment. As can be seen, the windows of greatest concern are Window 7 in the Air Cell and Windows 10 and 15 in the Argon Cell, which may receive gamma exposures at rates greater than 10^5 rad/hr.

*T. W. Eckels, L. F. Coleman, et al., Design and Performance of Shielding Windows and Cell Lighting FCF of EBR-II, ANL-7103.

After the shielding windows for the Fuel Cycle Facility were installed, there were cases reported (by a few operators of hot cells at various locations in the world) of damage to thick slabs of glass by the discharge of gamma-induced electrical charges (see Appendix I). It has since been learned that higher integrated gamma exposures are permissible if the glass surface is protected from any accidental blow and if the glass is maintained at elevated temperatures during gamma irradiation. Accordingly, the shielding windows of the two cells of the Facility have been modified by adding a 1/4-in.-thick cover plate, A', made of tempered cerium-stabilized lime glass, on each A Slab frame on the inner (cell) face. A gap of approximately 1/8 in. was left between the two glass surfaces. The cover plates will prevent any accidental impacts on the thick window panes and resultant disruptive discharges of gamma-induced electrical charges in the shielding windows.

A further beneficial effect may be anticipated. Because of the insulating effect of the gas space between the cover plate and the A Slab, the temperature of the A Slab will be raised. The protection afforded by the cover plate and the higher slab temperature should lengthen the useful life of the A Slab.

CALCULATION OF TEMPERATURE IN SHIELDING WINDOW DURING CELL OPERATION

The temperature profiles, the temperature extremes, and the thermal cycles in Fuel Cycle Facility shielding windows on which cover plates have been installed have been estimated. Such data were obtained with a view to setting limitations on the amount of radioactive material in the cells in order to prevent damage to the windows from excessive radiation.

For the purposes of temperature calculations, the following primary assumptions were made:

1. ambient cell temperature: 100°F;
2. ambient temperature in operating annulus: 75°F (the operating annulus is the corridor around the cell complex);
3. gamma exposure rate at inner wall faces of cell: 100 Btu/hr-ft^2, which is approximately equivalent to 3.5×10^5 rad/hr (see Appendix II);
4. steel shutters open 8 hr and closed 16 hr per day.

The problem is that of a series of semi-infinite slabs with variable internal heat sources. In calculating the data for the temperature profiles, the technique of finite differences[2] was used with depth increments of 2 in. and time increments of 0.485 hr. Terminology and equations are presented in Ref. 2 and Appendix III.

Calculations of gamma attenuation as used in the original design of the window shielding (see Appendix IV) were utilized to derive the internally generated heat for each thickness increment. Tables II and III show the calculated gamma transmittance and heat generation through a shielding window (1) for the window without a 1/4-in. glass cover plate and (2) for the window with a cover plate.

Estimates of the heat generated within the window (Tables II and III) were reduced appropriately for the shutter-closed condition.

TABLE II. Gamma Transmittance and Heat Generation[a] through Shielding Window. (No cover plate on A Slab and shutter open.)

		Heat Generation ($Btu/hr-ft^2$)	
Depth x (in.)	Transmittance T ($in.^{-1}$)	$Q\Delta x$	$\Sigma Q\Delta x$
1	0.513	48.7	48.7
2	0.564	22.4	71.1
3	0.580	12.1	83.2
4	0.595	6.8	90.0
5	0.610	3.89	93.9
6	0.623	2.30	95.21
7	0.633	1.39	96.60
8	0.644	0.854	98.454
9	0.654	0.535	98.989
10	0.661	0.343	99.332
11	0.668		
12	0.673		
13	0.678		
14	0.683	Δx = 1 in.	
15	0.685		
16	0.688		
17	0.690		
18	0.692		
19	0.693		
20	0.695		

[a]See Appendix II for derivation of the equivalence of 3.5×10^5 rad/hr to 100 $Btu/hr-ft^2$.

TABLE III. Gamma Transmittance and Heat Generation[a] through Shielding Window. (1/4-in.-thick glass cover plate on A Slab and with shutter open.)

		Heat Generation ($Btu/hr\text{-}ft^2$)	
Depth x (in.)	Transmittance T ($in.^{-1}$)	$Q\Delta x$	$\Sigma Q\Delta x$
-1/4	0.846	15.37	15.37
1	0.513	41.21	56.58
2	0.564	18.93	75.51
3	0.580	10.28	85.79
4	0.595	5.75	91.54
5	0.610	3.30	94.84
6	0.623	1.94	96.78
7	0.633	1.18	97.96
8	0.644	0.87	98.83
9	0.654	0.45	99.28
10	0.661	0.28	99.56

[a]See Appendix II for derivation of the equivalence of 3.5×10^5 rad/hr to 100 $Btu/hr\text{-}ft^2$.

RESULTS AND CONCLUSIONS

Temperatures at various depths into the windows under shutter-closed and shutter-open conditions were calculated. Calculations of temperatures in a window without a cover plate were for a 40-hr period. The calculations for a window with a cover plate were for 72 hr.

This information should be of use in considering any proposed changes in operating procedures used in the Fuel Cycle Facility as well as any equipment modifications which could affect the shielding windows.

Sample calculations of transient temperature profiles are presented in Appendix V, and sample calculations of steady-state temperature profiles are presented in Appendix VI. Figures 3 through 10 depict some of the calculated temperature profiles obtained in this study.

Figure 3 shows calculated thermal cycling over a 72-hr period at a point on the cell-side face of the A Slab, with the shutter opened and closed in the cycle of 8 hr open and 16 hr closed. Separate curves are presented for conditions in which the cover plate is present and absent. Note that each time the shutter is opened, a rapid decrease in temperature at the A Slab surface is expected in the absence of a cover plate.

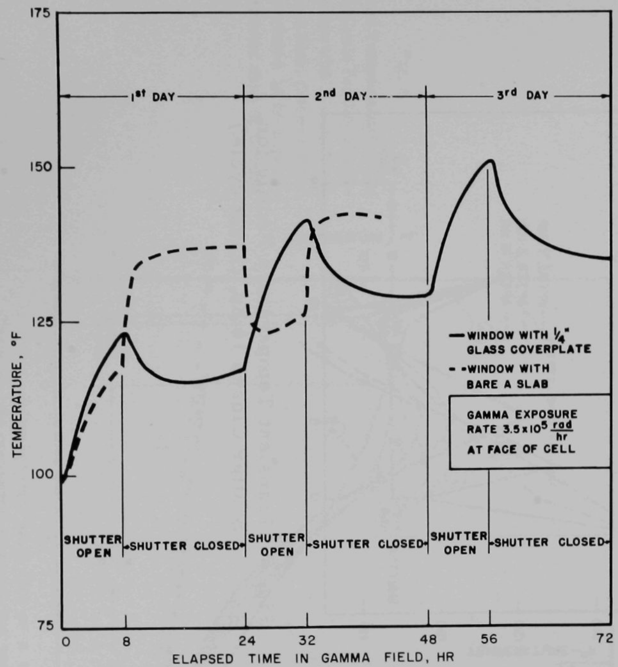

Fig. 3. Thermal Cycling of Point on Cell-side Surface of A Slab

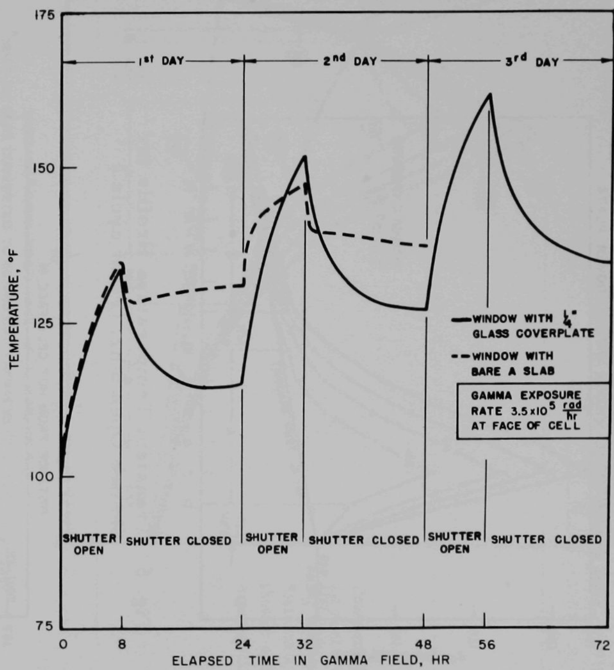

Fig. 4. Thermal Cycling of Point 2 in. from Cell-side Surface of A Slab

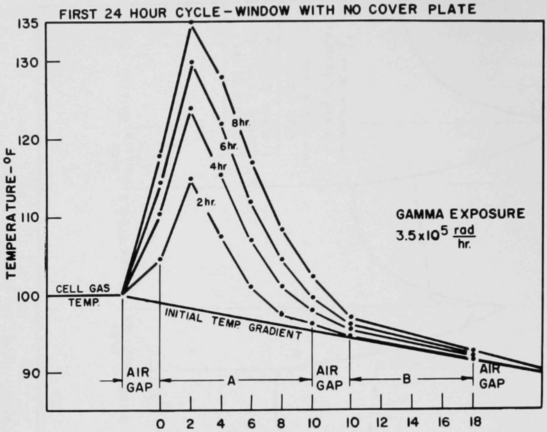

Fig. 5. Transient Temperature Profile for Shutter Open 8 hr. (First cycle.)

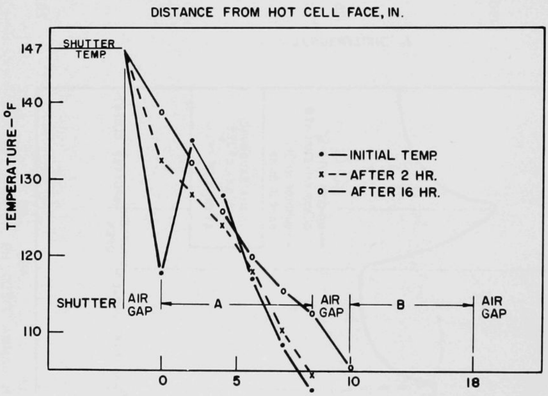

Fig. 6. Transient Temperature Profile for Shutter Closed 16 hr. (First cycle.)

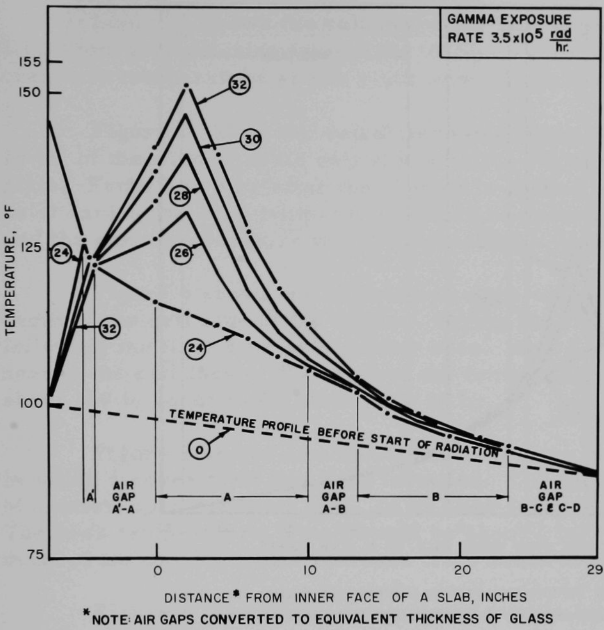

Fig. 7

Transient Temperature Profiles for Fuel Cycle Facility Shielding Window with 1/4-in. Cover Plate on A Slab. (Second cycle; shutter open 8 hr; cumulative exposure time 24 through 32 hr.)

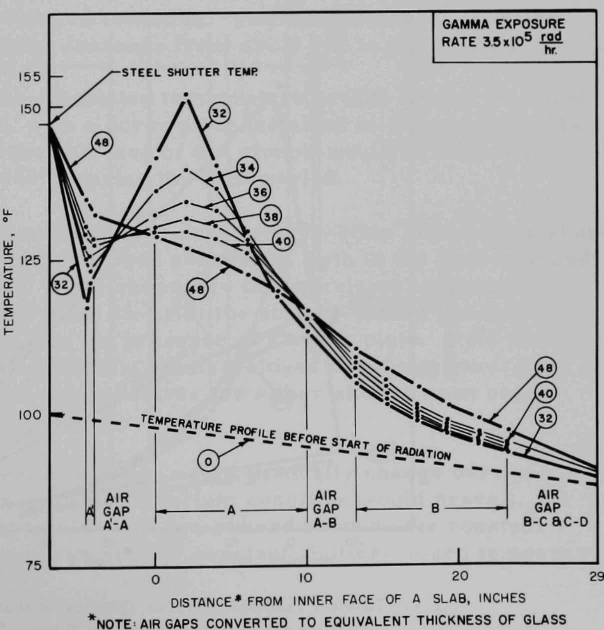

Fig. 8

Transient Temperature Profiles for Fuel Cycle Facility Shielding Window with 1/4-in. Cover Plate on A Slab. (Second cycle; shutter closed 16 hr; cumulative exposure time 32 through 48 hr.)

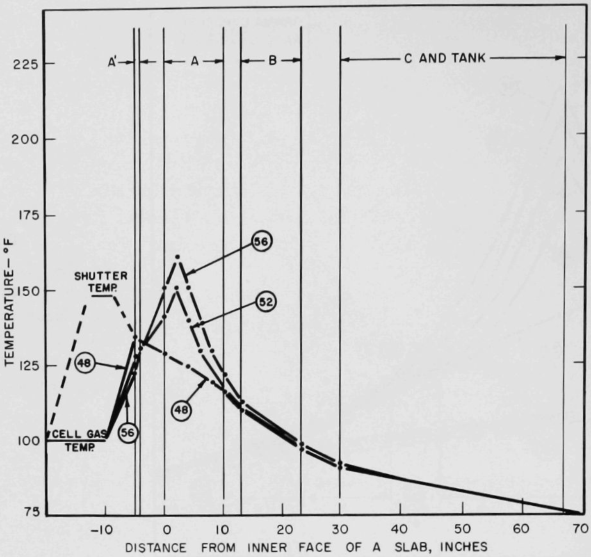

Fig. 9. Transient Temperature Profile. (Third cycle; shutter open 8 hr; cumulative exposure time 48 through 56 hr.)

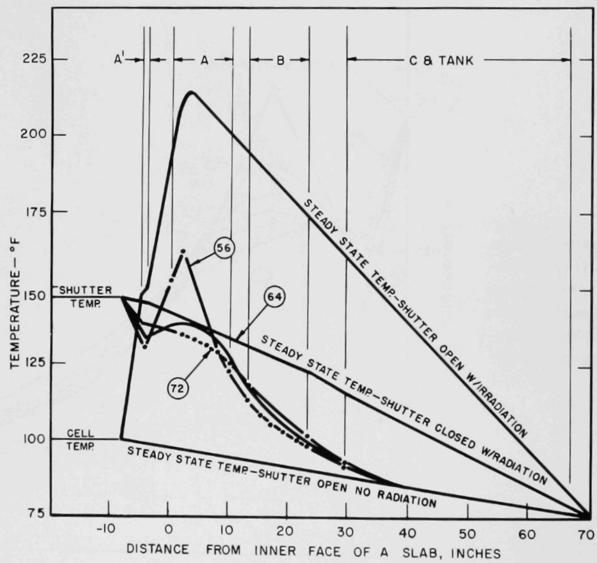

Fig. 10. Transient Temperature Profile. (Third cycle; shutter closed 16 hr; cumulative exposure time 56 through 72 hr.)

Figure 4 shows the calculated thermal cycling at a point in the A Slab 2 in. from the cell-side face of the A Slab. Note that there is a rapid decrease in temperature at this point when the shutter is closed.

Figure 5 shows the calculated temperature profiles through about 18 in. of the window at its cell side with the shutter open and with no cover plate. From 2 to 8 hr after the shutter is opened for the first cycle, the point having the peak temperature would be about 2 in. from the cell face, and the peak temperature would increase with time from about 115 to 135°F.

Figure 6 shows the calculated temperature profile to about a 10-in. depth at the cell side of the window, during the 16 hr with shutter closed following the first 8 hr with shutter open. At a 2-in.-depth of the glass, next to the cell face of the window, the temperature would increase from about 120 to about 140°F during the 16 hr.

Figure 7 shows a calculated temperature profile for 23 in. of window in which a cover plate has been installed. The plots are for the second 8 hr of shutter-open condition (i.e., 24 to 32 hr from the start of irradiation). The peak temperature, which would be about 2 in. from the cell face during most of the period, would increase from about 125 to about 150°F.

Figure 8 also shows a calculated profile for a 23-in. depth of a window on which a cover plate has been installed. The time period is for the second 16-hr shutter-closed condition. The temperature 2 in. below the cell face would gradually decrease from about 150 to about 125°F.

Figure 9 shows the calculated temperature profile during the third 8-hr shutter-open period, with a cover plate installed on the window. The temperature 2 in. inside the cell face of the window would be increased from about 125 to about 160°F during the 8-hr period.

Figure 10 shows curves of calculated steady-state profiles for shutter open constantly and shutter closed constantly, both in the presence and in the absence of radiation. Also shown are the calculated temperatures to a 40-in. depth during the third 16-hr of the shutter-closed condition. All of the curves are based on the presence of a cover plate. Note that the temperatures calculated for this shutter-closed cycle are generally lower than the steady-state temperatures for either shutter open constantly or shutter closed constantly.

This cyclic temperature range would gradually change over possibly a two-week period until a cyclic equilibrium condition would prevail. At that time the temperature would vary somewhere between the constant shutter-open temperature curve and the constant shutter-closed temperature curve.

From the calculated relationships, the principal thermal effects of installing the cover plate appear to be:

1. The peak temperature attained in the A Slab will apparently be raised by 35 to 40°F with a cover plate. A peak temperature of about 215°F will occur at $3\frac{1}{2}$-in. depth with a cover plate, as compared to a peak temperature of about 175°F at $4\frac{1}{2}$-in. depth without a cover plate (from the steady-state shutter-open curve of Fig. 10).

2. The maximum temperature gradient in the A Slab will be slightly less with a cover plate than without ($\sim$14.8°F/in. with a cover plate; 15.3°F/in. without).

3. After the shutter was closed, the temperature change near the surface of the A Slab was calculated to occur more rapidly in the absence than in the presence of the cover plate.

APPENDIX I

Damage to Shielding Windows from Irradiation

At the time the shielding windows for the Fuel Cycle Facility were being designed, there had been only one reported case of damage to a shielding window by the discharge of a gamma-induced electrical charge within a thick slab of glass. Since that time, there have been several additional such incidents. Experiments have since been performed at this Laboratory[3] and elsewhere[4] on shielding glasses exposed to radiation. The results obtained[5] in experiments on shielding glasses (PPG* 4966, 6788, and 6792; 3.3-g/cm^3 density; cerium oxide-stabilized glasses) have shown the following:

(1) Spontaneous discharges occur in 10 by 10 by 8-in.-thick glass samples irradiated, at room temperature, to integrated doses of 10^8 to 10^9 rad. (2) Discharges occur when 4-in. glass cubes are irradiated to integrated doses of 10^6 to 10^7 rad at room temperature, and then struck a bruising blow on the surface of the glass. (3) Measurements show significantly less accumulation of electrical charge in 4-in.-cube glass samples heated during irradiation to temperatures up to 140°F. When a sample was heated to 150°F during irradiation to an integrated dose of 1.6×10^7 rad and was then struck a bruising blow, a discharge did not occur.

It may not be possible to predict directly the effect of irradiation upon the shielding windows (PPG 6792 glass on the irradiated side) in the Fuel Cycle Facility from the results of these experiments, owing to differences in temperatures and in glass geometry. However, the results indicate that higher integrated gamma exposures will be permissible if the glass surface is protected from any accidental blow and if the glass is maintained at elevated temperatures during gamma irradiation.

The shielding windows of the Fuel Cycle Facility have each been modified by the installation of a 1/4-in.-thick glass plate, 39 in. square. It is mounted on the A Slab assembly and thus can be replaced remotely. The cover plates are tempered Pittsburgh Plate Glass Co. #6740 (a cerium-stabilized lime glass having a density of 2.7 g/cc). They were cut (before tempering) with corners of 2-in. radius.

*Products of Pittsburgh Plate Glass Company.

APPENDIX II

Transformation of Data from Radiation Units to Heat Units

The derivation for the equivalence of 3.5×10^5 rad/hr to 100 Btu/hr ft^2 (Q_0) follows. A power conversion equation[6] is

$$1 \text{ Btu hr}^{-1} = 1.82 \times 10^{12} \text{ MeV sec}^{-1}. \tag{1}$$

From this, it follows that

$$1 \text{ Btu hr}^{-1} \text{ ft}^{-2} = 1.96 \times 10^{9} \text{ MeV sec}^{-1} \text{ cm}^{-2}. \tag{2}$$

Also, values from a graph[6] of gamma flux equivalent to one R hr^{-1} as a function of gamma energy can be applied to each energy group of the assumed spectrum of Table I. Summing the products for each group gives 5.31×10^{11} MeV sec^{-1} cm^{-2} as the total. Then

$$1 \times 10^6 \text{ rad/hr} = \frac{5.31 \times 10^{11} \text{ MeV sec}^{-1} \text{ cm}^{-2}}{1.96 \times 10^{9} \text{ MeV sec}^{-1} \text{ cm}^{-2} \text{ Btu}^{-1} \text{ hr ft}^{2}}$$

$$= 270 \text{ Btu hr}^{-1} \text{ ft}^{-2}, \tag{3}$$

and for the assumed exposure for the shielding windows of 3.5×10^5 rad/hr, the total heat-generation potential (Q_0) will be

$$Q_0 = 0.35 \times 270 = 94.5 \cong 100 \text{ Btu hr}^{-1} \text{ ft}^{-2}. \tag{4}$$

APPENDIX III

Definitions, Abbreviations, and Constants

A. Terminology for Gamma Attenuation

I - Gamma intensity, rad/hr

I_0 - Incident gamma intensity

μ - Linear gamma attenuation coefficient, $in.^{-1}$

x - Depth in attenuating medium, in.

e - Napierian base

MeV - Energy of gamma ray

$I = I_0e^{-\mu x}$ - Equation for linear attenuation of monochromatic radiation

$T = I/I_0$ - Transmittance

B. Terminology for Heat Transfer

A - Cross-sectional area, sq ft

L - Thickness in direction of gamma-ray propagation, ft or in. as specified

h - Combined convection and radiant heat transfer coefficient (permissible in this limited temperature range)

k - Coefficient of thermal conductivity, Btu in./ft^2 °F

q - Rate of heat transfer, Btu/ft^2 hr

Δt - Temperature increment, °F

$\Delta\theta$ - Time increment, hr

Δx - Thickness increment

T_n - Temperature at a designated point, °F

$q = kA(\Delta t)/L$ - Basic equation of heat conduction

$q = hA(\Delta t)$ - Basic equation of heat convection

c - Heat capacity, Btu/lb °F

ρ - Density, lb/ft^3

°F - Degrees Fahrenheit

Adiabatic Wall - Surface through which there is no heat flow

C. Values Assigned to Constants for Gamma-attenuation Calculations

The following values are for PPG 4966, 6788, and 6792 glasses (3.3-g/cm^3 density lead glasses having CeO_2 contents, respectively, of 1.85, 0.85, and 2.4 w/o):

$$c = 0.133 \text{ Btu/lb °F at 100°F};$$

$$k = 0.416 \frac{\text{Btu ft}}{\text{hr ft}^2 \text{ °F}} = \frac{5.0 \text{ Btu in.}}{\text{hr ft}^2 \text{ °F}} = \frac{10 \text{ Btu-1/2 in.}}{\text{hr ft}^2 \text{ °F}};$$

$$\rho = 206 \text{ lb/ft}^3 \ (3.3 \text{ g/cm}^3).$$

Combined convection and radiation constants as follows:

$$\left\{\begin{matrix} h_1 \\ h_6 \end{matrix}\right. = 2.0 \left\{\begin{matrix} h_1\text{:} & \text{cell atmosphere to innermost surface; free convection;} \\ h_6\text{:} & \text{annulus atmosphere to outermost surface; free convection.} \end{matrix}\right.$$

$$h_1' = 1.8 \quad h_1'\text{: shutter to A' or to A}$$

$$\left\{\begin{matrix} h_2 \\ h_3 \\ h_4 \\ h_5 \end{matrix}\right. = 1.2 \left\{\begin{matrix} h_2\text{:} & \text{A' to A} \\ h_3\text{:} & \text{A to B} \\ h_4\text{:} & \text{B to C} \\ h_5\text{:} & \text{C to D} \end{matrix}\right\} \text{trapped gas space, 1/16 to 1/8 in. (between major window assembly)}$$

L_W = 57 in. = Total glass thickness of complete window

L_A = 10 in. = Glass thickness of A Slab

L_B = 10 in. = Glass thickness of B Slab

L_T = 37 in. = Glass thickness of tank unit and C pane combined.

APPENDIX IV

Calculation of Gamma Exposure Rates at Various Depths in Shielding Windows

For the evaluation of shielding-glass formulations during design of the shielding windows, estimates of the gamma exposure rate to be expected at each inch of depth in the window were obtained as follows. The familiar equation for penetration of a shield by monochromatic gamma radiation is

$$I = I_0 e^{-\mu x}. \tag{5}$$

Then, as for light, monochromatic transmittance per inch, T, for gamma rays is

$$T = I/I_0 = e^{-\mu x}, \tag{6}$$

where

μ = linear attenuation coefficient (in.$^{-1}$),

x = thickness of attenuating medium (one inch),

and

$$\log_{10} T = (10.000 - 0.4343\,\mu) - 10. \tag{7}$$

The exposure rate I at any desired depth x can be found from

$$\log I = \log I_0 + x[(10.000 - 0.434\,\mu) - 10]. \tag{8}$$

The sum of the antilogs for each energy group, then, is the total exposure rate at the thickness x. The ratio of this sum to the initial 1×10^6 rad/hr is the effective transmittance for this thickness to the complete gamma spectrum.

For the first inch,

$$T_1 = I_1/I_0 = 0.513.$$

For the 20th inch,

$$T_{20} = I_{20}/I_{19} = 0.695.$$

The amount of energy absorbed in an increment of thickness, Δx_1, as the gamma energy is converted to heat energy, is simply $Q_0 - Q_1 = q\Delta x_1$, where, in this case, the units are Btu/hr ft^2, and Q_0 and Q_1 represent the initial and remaining potential for heat generation.

APPENDIX V

Sample Calculations--Transient Temperature Profiles

The calculations* shown here are for the conditions of a window with a 1/4-in.-thick cover plate installed on the A Slab and for a period of time when the protective steel shutter is open. Figure 11 shows a number of the points for which the temperature is to be calculated. Calculation of temperatures in each glass unit is a separate problem with its own set of temperature points. As suggested by the arrangement in the figure, two adjacent panes of glass can be considered to have two temperatures in common.

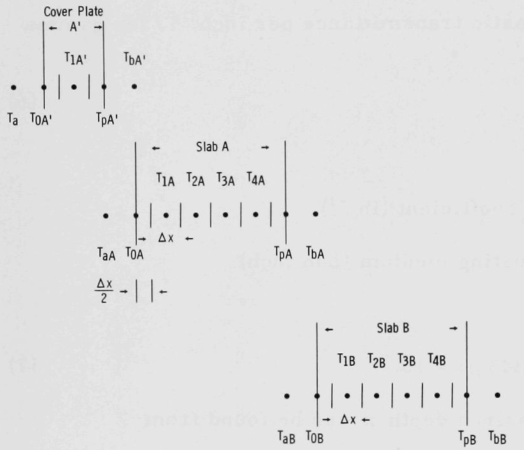

Fig. 11

Subdivision Scheme Used for Glass Slabs A', A, and B in Temperature Calculations

T_a - ambient cell temp
$T_{0A'}$ - present temp of point 0A' (on surface of A')
$T_{1A'}$ - present temp of point 1A' (midthickness of A')
$T_{pA'}$ - present temp of point pA' (on back surface of A')
$T_{bA'}$ - present temp of point bA' (ambient gas temp behind A')
T_{aA} - present temp of point aA (ambient gas temp in front of A)
T_{0A} - present temp of point 0A (on front surface of A)
T_{1A} - present temp of point 1A (midpoint of first full Δx in A)
T_{2A} - present temp of point 2A (midpoint of second full Δx in A)

The finite-difference method of transient-temperature calculation presumes that the future temperature of a point is some function of the present temperature of that point and of adjacent points. Let T'_{0A} represent the temperature of point 0A after a time increment $\Delta\theta$. Then

$$T'_{0A} = F_{a0}Ta + F_{10}T_{1A} + F_{00}T_{0A} + G_{0A}, \qquad (1)$$

when the F_{nn}'s are weighting factors whose sum is 1, and G is a heat-generation term. Heat generation is presumed to occur only in full Δx increments:

*See Appendix III for definitions, abbreviations, and constants.

$$G_{nn} = q\Delta x/kM, \tag{2}$$

where

q = quantity of heat created by absorption of gamma energy in that Δx

k = coefficient of thermal conductivity

M = modulus (defined below)

$$F_{a0} = K_{a0}\Delta\theta/C_0 \tag{3}$$

$$K_{a0} = h_1 A$$

$$C_0 = \tfrac{1}{2}A\Delta x c\rho$$

$$F_{a0} = \frac{2h\Delta\theta}{c\rho\Delta x} = 2\frac{h\Delta x}{k}\frac{k}{c\rho}\frac{\Delta\theta}{\overline{\Delta x}^2} = 2\frac{N_{Bi}}{M} \tag{4}$$

$$N_{Bi} \equiv h\Delta x/k$$

$$M \equiv c\rho\overline{\Delta x}^2/k\Delta\theta$$

$$F_{10} = 2k\Delta\theta/c\rho\overline{\Delta x}^2 = 2/M \tag{5}$$

$$F_{00} = 1 - F_{a0} - F_{10}. \tag{6}$$

The modulus M should be an integer to make computations simple. For this problem, let $M = 4$. To avoid negative or zero weighting factors, $M > 2 + 2\,N_{Bi}$. For simple computations, N_{Bi} should be the decimal equivalent of some common fraction. The time increment $\Delta\theta$ must be the same for all sections of the computations. For the major window components, Δx = 2 in. = 0.167 ft. If the convection coefficient h_2 is chosen to be 1.25, then

$$N_{Bi0A} = \frac{h_2\Delta x}{k} = \frac{1.25(0.167)}{0.416} = 0.5 = 1/2.$$

From (4),

$$\Delta\theta = \frac{c\rho}{k}\frac{\overline{\Delta x}^2}{M} = \frac{0.138(206)}{0.416}\frac{(0.167)^2}{4} = 0.475 \text{ hr}.$$

The weighting factors for the cover plate can now be calculated. The face of this plate exposed to the cell atmosphere has free convection, so $h \cong 2.0$. For simplifying the computation, assume $h = 2.08$ and that $\Delta x = 0.6$ in. = 0.05 ft. Then

$$N_{Bi0A'} = \frac{2.08(0.05)}{0.416} = 0.25 = 1/4.$$

Under the assumptions for heat generation:

$$G_{0A'} = G_{pA'} = 0;$$

$$G_{1A'} = \frac{q\Delta x}{kM} = \frac{15.4(0.05)}{0.416\ M} = \frac{1.83°F}{M},$$

since, from Table III, $q = 15.4$ Btu/hr ft^2. Then, from Equations 3, 4, and 5,

$$F_{a0} = \frac{2N_{Bi}}{M} = \frac{2(1/4)}{M} = \frac{1/2}{M} = \frac{1/2}{4};$$

$$F_{10} = \frac{2k\Delta\theta}{c\rho\overline{\Delta x}^2} = \frac{2}{M} = \frac{2}{4};$$

$$F_{00} = 1 - F_{a0} - F_{10} = \frac{4}{4} - \frac{1/2}{4} - \frac{2}{4} = \frac{3/2}{4}.$$

Finally,

$$T'_{0A'} = \frac{1/2T_a + 3/2\ T_{0A'} + 2\ T_{1A'}}{4}. \tag{7}$$

By a similar procedure, the weighting factors for determining T'_{1A} and $T'_{pA'}$ can be established. The equations for $T'_{1A'}$ and $T'_{pA'}$ are

$$T'_{1A'} = \frac{T_{0A'} + 2\ T_{1A'} + T_{pA'} + 1.83}{4}; \tag{8}$$

$$T'_{pA'} = \frac{2\ T_{1A'} + 1.7\ T_{pA'} + 0.3\ T_{bA'}}{4}. \tag{9}$$

As mentioned earlier in discussing Fig. 11, $T_{pA'}$ (the temperature of the rear face of cover plate A') can be considered to be the ambient gas temperature in contact through a convection film thickness with the front face of Slab A. Also, T_{0A} (the temperature of the front face of Slab A) can be considered to be the ambient gas temperature in contact with the rear face of A'.

The initial equilibrium temperature profile existing at time zero is assumed to be that resulting from an ambient cell temperature of 100°F and an ambient air temperature in the operating annulus of 75°F (see Fig. 10).

Part of a transient-temperature calculation is shown in Table IV. For this problem, the temperatures were calculated for 21 points. The first point was a constant 100°F (ambient cell temperature). The 21st point was at a depth of $28\frac{1}{4}$ in. of glass, for which the initial temperature was 84.9580°F.* The heat generation due to gamma radiation at this depth was calculated to contribute a temperature rise of 0.0003°F/M per time increment.

TABLE IV. Example of Transient-temperature Calculations. Window with 1/4-in. glass cover plate; shutter open.

	Line	Cell Temp (T_a)	Surface Temp of Cover Plate, Hot Side ($T_{0A'}$)	Temp at Midsection of Cover Plate ($T_{1A'}$)	Surface Temp of Cover Plate, Cold Side ($T_{pA'}$)	Surface Temp of A Slab, Hot Side (T_{0A})	Temp of A Slab at Depth of 2 in. (T_{1A})	Temp of A Slab at Depth of 4 in. (T_{2A})
Temp at Time = 0	1	A	B	C	D	E	F	H
	2		1/2 B	C	0.7 D	-	F	
	3		1/2 A	B	2 C	D	E	
	4		2 C	D	0.3 E	2 F	H	
Heat Generation	5		-	G_1	-	-	G_2	
Temp at	6		Sum	Sum	Sum	Sum	Sum	
Time = 1	7	A	1/4 Sum	1/4 Sum	1/4 Sum	1/4 Sum	1/4 Sum	
	Weighting Factors		1/2; 3/2; 2	1; 2; 1	2; 1.7; 0.3	1; 1; 2	1; 2; 1	
				Numerical Values Following Schedule Shown Above				
$\Sigma\theta = 0$	1	100.0000	99.2500	99.0650	98.8800	97.6150	96.9820	96.4390
	2		49.6250	99.0650	19.2160	-	96.9820	
	3		50.0000	99.2500	198.1300	98.8800	97.6150	
	4		198.1300	98.8800	29.2845	193.9640	96.4390	
	5		-	1.8300	-	-	26.1960	
	6		397.0050	398.0900	395.5105	390.4590	414.1240	
$\Sigma\theta$ = 0.475 hr	7	100.0000	99.2512	99.5225	98.8776	97.6147	103.5310	97.7672
	8		49.6256	99.5225	69.2143	-	103.5310	
	9		50.0000	99.2512	199.0450	98.8776	97.6147	
	10		199.0450	98.8776	29.2844	207.0620	97.7672	
	11		-	1.8300	-	-	26.1960	
	12		397.9218	399.0038	396.4213	403.5543	428.6344	
$\Sigma\theta$ = 0.950 hr	13	100.0000	99.4804	99.7509	99.1053	100.8856	107.1600	

For the first roughly 8-hr period, there were 16 time increments of 0.475 hr each, totalling 7.6 hr. There were 336 individual six-line calculations to be performed. Initial conditions are shown on line 1. The seventh line is the new temperature condition after the first time increment. The top part of the table uses letters to represent the values and illustrates the computation scheme in accordance with Equations 6, 7, and 8, respectively, for columns 2, 3, and 4 of the table. The derivations of the equations for T_{0A} and T_{1A} were not shown. The bottom portion of the table shows the numerical values obtained by following the schedule of the top portion.

Since such a procedure is tedious, there is a fairly high probability of making mistakes. A mistake will affect all subsequent calculations in the vertical column in which it originally occurs and will fan out at a 45° angle downward through adjacent columns. A second table was made which was very useful in uncovering errors in the calculations. Three columns are required for each of the 21 points, and one line is used for each time

*Six significant figures are used only to maintain the proper relations among temperatures at the various points.

increment. In the first column of this table was recorded the temperature of a point at the end of each time increment. The second column recorded the increment in temperature from the previous period. The third column recorded the change from the temperature increment for the preceding time increment. In effect, the values shown in the second and third columns were velocity of temperature change and acceleration. Since a finite-difference method was employed, the values during the first few time increments exhibited abnormal perturbations, but in subsequent time increments a sort of predictable "wave movement" of the numerical values in the acceleration column made it easy to spot gross errors in the temperature calculations. About 36 hr were expended in calculating the thermal behavior of the window for the 72-hr period of cell operation under scrutiny.

Some justification should be given for the procedure used in calculating the temperature of the 1/4-in.-thick cover plate, since the procedure used violates some of the rules for the finite-difference method. A modulus (M) of 4 was desirable in order to have a single divisor amenable to the mental calculation of quotients.

Temperature values for the cover plate were achieved which varied with time in a reasonable manner without oscillation if the following assumptions were used:

(1) The glass thickness was 1.2 in., with $\Delta x = 0.6$ in. for this part of the calculation.

(2) The heat generation from gamma absorption was retained at 15.4 Btu/hr ft^2, which value had been calculated as the generation within a 1/4-in. cover plate.

(3) A modulus of $M = 4$ and a time increment of $\Delta\theta = 0.475$ hr were used as in the remainder of the calculations, even though the equation $M = c\overline{\Delta x}^2/k\Delta\theta$ was not satisfied.

To abide by the rules completely would have required $\Delta x = 1/8$ in. for all calculations as compared with $\Delta x = 2$ in. used for the remainder of the calculations. Consequently, the time increment would be only 1/256 of ~1/2 hr, which change would have increased the number of calculations enormously.

At the end of the 72-hr period, the transient-temperature profile curve was approaching the independently calculated temperature profiles for equilibrium conditions with shutter constantly open, and for shutter constantly closed, as is shown in Fig. 10.

It would appear that rigid adherence to the rules in the calculation of the cover-plate temperature could change only one variable markedly--the time to equilibrium. By inspection, it would appear this time might in reality be shorter than indicated in these calculations.

APPENDIX VI

Sample Calculations* of Steady-state Temperature Profile through a Window under the Conditions of Shutter Constantly Open, with and without a Cover Plate

For heat conduction,

$$q = kA\Delta t/L, \tag{1}$$

where

$$A = 1\ \text{ft}^2;$$

$$k = 5.0\,\frac{\text{Btu in.}}{\text{ft}^2\ {}^\circ\text{F}} = 10\,\frac{\text{Btu-}1/2\ \text{in.}}{\text{ft}^2\ {}^\circ\text{F}};$$

$$L = \text{thickness, in.}$$

$$\Delta t = \text{temperature difference, }{}^\circ\text{F}.$$

Also,

$$\Delta t_{\text{conduction}} = qL/k. \tag{2}$$

For heat convection and radiation,

$$q = hA\Delta t. \tag{3}$$

Then for unit area

$$\Delta t_{\text{convection}} = q/h_i \tag{4}$$

where

$$\begin{cases} h_1 = 2.0 \\ h_2 = 1.8 \\ h_3 = h_4 = h_5 = 1.2 \\ h_6 = 2.0. \end{cases}$$

If edge effects are neglected, this is a one-dimensional heat transfer problem with a series of finite slabs separated by air gaps. In the conversion of gamma energy to heat energy, the slabs are considered to have internal heat sources which decrease exponentially in intensity with increasing depth.

*See Appendix III for definitions, abbreviations, and constants.

It is possible to get a fairly accurate location of the peak temperature and its value by simple arithmetic when it is recalled that the peak temperature will occur at an adiabatic wall (see Fig. 12). All heat generated within the glass to the left of the adiabatic wall will be rejected to the cell gas, while all the heat generated to the right of the wall will be rejected to the operating annulus air. (This operating annulus is the corridor surrounding the argon-atmosphere and air-atmosphere cells.) A few successive approximations will satisfy the equations to give a common peak temperature.

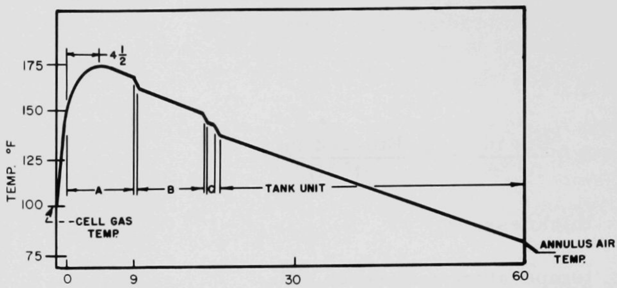

Fig. 12. Equilibrium Temperature Profile for Shielding Window without a Cover Plate; Steel Shutter Open Constantly; Gamma Exposure Rate 3.5 x 10^5 rad/hr

From the left, the peak temperature will be

$$T_{max_1} = T_{cell} + \Sigma\Delta t_{convection} + \Sigma\Delta t_{conduction}. \tag{5}$$

Proceeding from the right, the peak temperature will be

$$T_{max_2} = T_{annulus} + \Sigma\Delta t_{convection} + \Sigma\Delta t_{conduction}. \tag{6}$$

If it is assumed that all of the remaining gamma energy is absorbed and converted to heat in the first Δx to the right of the adiabatic wall, the last term will become qL/k where q is the heat equivalent of the remaining gamma energy, L is the total glass thickness less the distance to the adiabatic wall from the left, and k is the thermal conductivity coefficient.

Tables V and VI display the amount of heat generated in each Δx (thickness increment) and the calculated summation of heat to be rejected to the left by each Δx. Table V is for the window without a cover plate, while Table VI is for a window with a 1/4-in.-thick cover plate.

TABLE V. Gamma-ray Heat Generation within A Slab; No Cover Plate; Shutter Open

Gamma Exposure Rate, 3.5 x 10^5 rad/hr (100 Btu/ft^2 hr)

Δx = 1/2 in.

Assumed Location of Adiabatic Wall Depth (in.)	Location of Δx, in. of depth									
	1/2	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$	5
	Δq, heat generated in Δx, Btu/hr ft^2									
	30	20	12	9.0	6.5	5.0	4.5	3.0	2.3	1.7
	$\Sigma\Delta q$, heat rejected to left, Btu/hr ft^2									
5	94	64	44	32.0	23.0	16.5	11.5	7.0	4.0	1.7
$4\frac{1}{2}$	92.3	62.3	42.3	30.3	21.3	14.8	9.8	5.3	2.3	
$4\frac{1}{4}$	91.5	61.5	41.5	29.5	20.5	14.0	9.0	4.5	1.5	
4	90.0	60.0	40.0	28.0	19.0	12.5	7.5	3.0		

Direction of Heat Flux

TABLE VI. Gamma-ray Heat Generation within A Slab with 1/4-in. Cover Plate; Shutter Open

Gamma Exposure Rate, 3.5 x 10^5 rad/hr (100 Btu/hr ft^2)

Δx = 1 in.

Assumed Location of Adiabatic Wall Depth (in.)	Location of Δx, in. of depth										
	-1/4	1	2	3	$3\frac{1}{2}$	4	5	6	7	8	9
	Δq, heat generated in Δx, Btu/hr ft^2										
	15.4	41.21	18.93	10.28	3.56	2.70	3.30	1.94	1.18	0.87	0.45
	$\Sigma\Delta q$, heat rejected, Btu/hr ft^2										
4	92.08	76.68	35.43	16.54	6.26	2.70	3.30	5.24	6.42	7.29	7.74
$3\frac{1}{2}$	89.38	73.98	32.77	13.84	3.56	2.70	6.00	7.94	9.12	9.99	10.44
3	85.82	70.42	29.21	10.28	3.56	6.26	9.56	11.50	12.68	13.55	14.00

Direction of Heat Flux

A. Window without Cover Plate

1. Assume peak temperature at the $4\frac{1}{4}$-in. depth. Using Table V and Equation 5, we obtain

$$T_{max_1} = T_{cell} + \Delta t_{convection} + \Sigma\Delta t_{conduction}$$

or

$$T_{max_1} = 100 + \frac{91.5}{2}$$

$$+ \frac{(91.5 + 61.5 + 41.5 + 29.5 + 20.5 + 14.0 + 9.0 + 4.5 + 1.5)}{10}$$

$$= 100 + 45.75 + 27.36 = 173.11°F.$$

Now,

heat rejected to annulus air = 100 - 91.5 = 8.5 Btu/hr ft^2.

Using Equation 6,

$$T_{max_2} = 75 + \frac{8.5}{2} + 3\left(\frac{8.5}{1.2}\right) + \frac{8.5(57 - 4.25)}{5}$$

$$= 75 + 4.25 + 21.5 + 89.67 = 190.4°F$$

so that

$$T_{max_2} - T_{max_1} = 190.4 - 173.1 = 17.3°F.$$

2. A second trial, assuming peak temperature at $4\frac{1}{2}$ in., yields

$$T_{max_1} = 174.2°F;$$

$$T_{max_2} = 177.0°F;$$

$$T_{max_2} - T_{max_1} = 5.2°F.$$

3. A third trial, assuming peak temperature at 5 in., yields

$$T_{max_1} = 177.3°F;$$

$$T_{max_2} = 155.2°F;$$

$$T_{max_2} - T_{max_1} = -22.1°F.$$

From the above three approximations, it can be seen that the peak temperature will occur at a depth slightly greater than $4\frac{1}{2}$ in. and that the peak temperature will be about 175°F. Figure 12 shows the temperature profile in a pictorial manner.

B. Window with a Cover Plate

An approximate peak temperature for steady-state temperature of the window with a cover plate can be calculated in a very similar manner, by means of Table VI and an assumption that the peak temperature occurs at a depth of $3\frac{1}{2}$ in.

Approaching T_{max} from the left:

$$T_{max_1} = T_{cell} + \Delta t_{convect_1} + \Delta t\ conduct_{cover\ plate} + \Delta t_{convect_2}$$

$$+ \Sigma\Delta t_{conduct_A} \leftarrow (0 \text{ to } 3\tfrac{1}{2} \text{in.})$$

$$= 100 + \frac{89.38}{2} + \frac{89.38}{20} + \frac{73.98}{1.8} + \frac{(73.98 + 32.77 + 13.84 + 3.56)}{5}$$

$$= 100 + 44.7 + 4.47 + 41.20 + 24.83$$

$$= 215.2°\text{F}.$$

Approaching T_{max} from the right:

$$T_{max_2} = T_{annulus} + \Delta t_{convect_4} + \frac{qL_{tank}}{k} + \Delta t_{convect_{4+5}}$$

$$+ \Sigma\Delta t_{conduct_B} + \Delta t_{convect_3} + \Sigma\Delta t_{conduct_A} \rightarrow (3\tfrac{1}{2} \text{ to } 10 \text{ in.})$$

$$= 75 + \frac{10.62}{2} + \frac{10.62(37)}{5.0} + \frac{20.88}{1.2} + \frac{10.44(10)}{5} + \frac{10.44}{1.2}$$

$$+ \frac{(2.7 + 6.0 + 7.94 + 9.12 + 9.99 + 10.44)}{5.0}$$

$$= 75 + 5.31 + 78.5 + 17.4 + 20.88 + 8.70 + 9.24$$

$$= 215.03°\text{F}.$$

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